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Relativistic Electron Beam Interactions for Generation of High Power at Microwave Frequencies

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    During the last few years, the application of intense, relativistic-electron beams to the generation of electromagnetic radiation at wavelengths ranging from 10 cm down to fraction of a millimeter has enabled significant advances to be made in peak power capabilities. The purpose of this review is to summarize the status of these advances and to describe briefly the nature of the several mechanisms involved.

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CONTENTS

RELATIVISTIC ELECTRON BEAM INTERACTIONS FOR GENERATION

OF HIGH POWER AT MICROWAVE FREQUENCIES*

I.   INTRODUCTION

During the last few years, the application of intense, relativistic-electron beams to the generation of electromagnetic radiation at wavelengths ranging from 10 cm down to fraction of a millimeter has enabled significant advances to be made in peak power capabilities. The purpose of this review is to summarize the status of these advances and to describe briefly the nature of the several mechanisms involved.

II. CONVENTIONAL MECHANISMS

In Fig. 1 are shown the record levels of peak power that have been achieved with the intense-beam technology. The results can be conveniently divided into three classes of experiments. First are experiments using traditional microwave mechanisms, particularly the klystron, backward-wave oscillator and magnetron geometries. In one experiment by Friedman,[1] a strongly modulated, axial, relativistic beam was used to generate a 500 MW signal at 3 GHz with a klystron-like series of resonant cavities. The efficiency was about 20%. Recent experiments

1

by Professor Bekefi and co-workers at MIT,[2] and more recent experiments

with MIT/NRL collaboration,[3] have shown that a straightforward magnetron

geometry yields peak-power levels up to about 4 GW. The efficiency in

these magnetron experiments is in the range of 25% to 35% and can prob-

ably be increased. These traditional devices are suitable for generat-

ing high power at frequencies below about 10 GHz. Above that frequency

the power density, losses and breakdown problems are too severe.

III. ELECTRON CYCLOTRON MASER (GYROTRON)

The second class of experiments are those based on the electron

cyclotron maser, called the gyrotron in the Soviet Union. This device

represents a major breakthrough for frequencies above 10 - 20 GHz and

extending to 300 GHz or more. Basic understanding of the device pro-

ceeded slowly following the early concepts and experiments. However,

recent developments in this country and in the Soviet Union have shown

that the cyclotron maser is ready for practical development.

(a) Description of the Process and Early Developments:

The electron cyclotron maser ideally consists of a cloud of

monoenergetic electrons in a fast wave structure such as a metallic tube

or waveguide, with electron velocity transverse to an applied axial

magnetic field. Such an electron ensemble can react unstably with a

fast microwave signal propagating through the waveguide. Initially, the

phases of the electrons in their cyclotron orbits are random, but phase

bunching can occur because of the relativistic mass change of the elec-

trons. Those electrons that lose energy to the wave become lighter and

accumulate phase lead while those electrons that gain energy from the

wave become heavier and accumulate phase lag. This can result in a

2

phase bunching such that the electrons radiate coherently and amplify the electromagnetic wave. Energy transfer from the electrons to the wave is optimized when the wave frequency is just slightly higher than the electron cyclotron frequency (or its harmonics). Early descriptions of this maser process are to be found in the works of Twiss,[4] Schneider,[5] and Gapanov.[6]

From the above description, it is clear that the cyclotron maser emits radiation at a wavelength determined by the strength of an applied magnetic field, and not by the dimensions of some resonant structure. Thus, unlike other microwave generators, the internal dimensions of the device may be large compared to the wavelength, and high power handling capability (up to megawatts) becomes compatible with operation at millimeter wavelengths. Indeed, the highest recorded millimeter-wave power, both peak and average, has been achieved with cyclotron masers.

The first unequivocal experimental demonstration of the cyclotron maser mechanism was made in 1964 by Hirshfield and Wachtel.[7] Their 5 kV, 200 μA electron beam was passed through a combination of a "corkscrew" static magnetic field and a magnetic hill; the electrons were then injected into a high-Q cylindrical cavity resonant at 5.8 GHz with most of their energy transverse to the axial magnetic field. Later a two-cavity "gyro-klystron" experiment was reported[8] which showed that an amplifier configuration was possible based on the same transverse bunching mechanism, only now the bunching is allowed to continue ballistically between input and output cavities. Other early work extended frequency into the millimeter wave and even the submillimeter

3

wave regime; an extensive description of this early work is contained in the review by Hirshfield and Grantstein.[9] However, in all of the early experiments, the promise of exceptionally large millimeter wave power was not realized, the best result being that of Bott who generated several watts of power at $2 \text{ mm} \leqslant \lambda \leqslant 4 \text{ mm}$.[10]

(b) Intense Relativistic Electron Beam Studies (High Peak Power Millimeter Waves):

New impetus to the study of the cyclotron maser mechanism came from the research into microwave emission from intense, relativistic electron beams, with beam power in the range $10^9 - 10^{12}$ W. A number of experiments, mainly at the Naval Research Laboratory, demonstrated that intense microwave radiation could be produced by perturbing the externally applied magnetic field which guided the electron beam.

This magnetic field perturbation took a number of forms, viz. a periodic magnetic ripple of limited length,[11-14] a nonadiabatic convergence of the magnetic field lines,[15] and a nonadiabatic divergence of the magnetic field lines.[16,17] A definitive identification of the cyclotron maser mechanism as the major source of microwave generation in these experiments was made through two salient observations. First, it was established[16,17] that the modal structure of the microwaves corresponded to that expected in the cyclotron maser instability. Secondly, it was demonstrated[11] that wave growth took place in a region of uniform magnetic field after the electron beam had encountered the magnetic perturbation. The perturbation in the magnetic field provided the required distribution of transverse kinetic energy, much as the magnetic corkscrew functioned in the early low power level experiments.

4

Table I displays the maximum attained peak power levels produced with intense relativistic electron beams through the cyclotron maser process. It is especially noteworthy that these record peak powers were produced at millimeter wavelengths as well as in the more usual microwave bands.

Table 1 - Peak power levels from cyclotron masers driven by intense relativistic electron beams.

Wavelength (mm)	Peak Microwave Power (MW)	Accelerating Voltage (MV)	Diode Current (kA)	Reference
40	900	3.3	80	14
20	350	2.6	40	13
8	8	0.6	15	42
4	2	0.6	15	42

In addition to the high power levels in these intense beam experiments, it was also demonstrated[16] that the emission possessed a high degree of temporal and spatial coherence. Furthermore, the cyclotron maser was operated as a distributed-interaction amplifier[18] which could be tuned magnetically over a wide frequency range. The amplifier configuration is shown in Fig. 2. It should be noted that a distributed-interaction device has the advantage of tunability over a wide frequency range, and in addition, allows dissipation of far greater power as compared with a short resonator. Thus, its realization has considerable practical importance.

Experimental research on cyclotron masers using intense relativistic electron beams is summarized in review papers by Hammer, et al.[19] and by Granatstein, et al.[20] Equally important as the experimental results was the stimulation they provided for theoretical studies.[21-23] We note especially the nonlinear analysis of the saturation of the cyclotron maser instability by phase trapping[22] and the subsequent self-consistent analysis,[23] which generalized the first result to include saturation by energy depletion as well as by phase trapping. The latter work is useful not only in interpreting intense relativistic electron beam experiments but also in developing practical cyclotron maser tubes driven by electron beams with more conventional parameters.

(c) USSR Studies Using Magnetron Injection Guns (High Average Power Millimeter Waves):

The lead in development of practical cyclotron masers using electron beams with conventional voltage and current values has been taken by a group working at the Gork'ii State University (USSR), where the device has been given the name "gyrotron". In contrast to the cyclotron maser work in the USA after 1970 which centered around the intense relativistic electron beam technology outlined above which was very much in the nature of a basic laboratory study, the Soviet work comprised a very intense development effort leading to practical power tubes at millimeter and submillimeter wavelengths. The key element in achieving practical devices characterized by high efficiency was in careful design of the electron gun. In the Gork'ii studies a crossed field, or so-called magnetron injection gun was used to launch an annular beam with a large fraction of energy transverse to the axis and

with minimum energy spread. These guns employed thermionic cathodes for CW and long-pulse operation. Experimental work on nonuniform cross section open resonators to optimize beam coupling for high efficiency has also taken place. All together, these developments have led to the announcement of the operation of two classes of devices, those operating in high (superconducting) magnetic fields, and those operating in lower conventional fields. Table 2 summarizes the results published to date on tubes of the first class.[24] Figure 3 is a drawing of a device of the second class, built by Kisel', et al.[25] This latter device in a magnetic field of only 6 kG, produced 9 mm CW power of 10 kW with 40% efficiency, and pulsed power of 30 kW at 43% efficiency. Recent reports from Soviet scientists who use the gyrotrons for RF heating of tokamak plasmas indicate that millimeter wave gyrotrons are now available with power approaching one hundred kilowatts.[26]

In parallel with the device development work there has been a strong Soviet theoretical effort. Account has been taken of the electron space charge,[27] nonuniform electromagnetic fields of the resonator structure in a full nonlinear treatment,[28] and of gyro-harmonic operation.[29]

(d) The Current NRL Program:

The success achieved in the USSR in realizing high efficiency gyrotrons has now stimulated parallel work in the USA. Under ERDA sponsorship, Varian Associates are currently developing a tube at 28 GHz with a CW power level of 200 kW for use in microwave-generated plasma studies at the Oak Ridge National Laboratory. This device is of the gyroklystron type[8] employing resonant cavities separated by drift spaces.

7

Table 2 - Reported gyrotron operating conditions and output parameters.[24]

Model No.	Cavity Mode	Wavelength mm	Cyclotron Harmonic Number	B-field kG	Beam Voltage kV	C. W. Power kW	Measured Eff., %	Theoretical Eff., %
1	TE_{021}	2.78	1	40.5	27	12	31	36
2	TE_{031}	1.91	2	28.9	18	2.4	9.5	15
	TE_{231}	1.95	2	28.5	26	7*	15	20
3	TE_{231}	0.92	2	60.6	27	1.5	6.2	5

* pulsed

8

The work at NRL is concentrating on millimeter wavelengths and on addressing scientific and technical issues at the limits of the technology. Currently studies are underway with the near-term goal of demonstrating an efficient 200 kW amplifier at λ = 8 mm. The device configuration to be emphasized in this effort is the distributed, traveling-wave amplifier (gyro-TWA) similar to that shown in Fig. 3 because of its advantages in handling high power. The field strengths encountered for a given power level will be considerably lower in a traveling wave device than in a device employing resonant cavities. Among the scientific issues to be addressed are the effect of self-fields of the electron beam and suppression of spurious mode generation in overmoded waveguide.

The advanced nonlinear theory of Sprangle and Drobot[23] has been adapted to cylindrical geometry[30] and used in obtaining a device design optimized for maximum efficiency. In this theory[23] it is shown that a threshold for the cyclotron maser instability exists at low energy (typically 10 - 20 keV transverse kinetic energy); at energies just above the threshold the process becomes saturated because the growth rate goes to zero as the transverse energy is depleted, and approaches the threshold value. At higher energies, on the other hand, a quite different saturation mechanism occurs. As energy is removed from the electrons the cyclotron frequency increases until the gyrating electrons are trapped in a phase such that energy transfer ceases. Competition between the two mechanisms leads to a peak in efficiency as a function of beam transverse energy. The plot of efficiency vs transverse energy which was used in designing the 200 kW distributed

amplifier at $\lambda = 8$ mm is shown in Fig. 4. Efficiency is seen to reach
a peak value of 70% in these beam frame calculations. The corresponding
efficiency of transferring beam energy to wave energy in the laboratory
frame is 51% for the design value of $V_\perp/V_{||} = 1.5$.

Realization of this high efficiency requires spread in elec-
tron transverse velocity no larger than a few percent, and thus, very
exacting design of the electron gun. A numerical code for tracing elec-
tron trajectories has been developed at NRL[31] and used in the design of
a magnetron injection gun for the 200 kW, 8 mm maser. A near-optimum
electrode configuration together with some representative electron
trajectories is shown in Fig. 5. For this gun design the spread in
transverse velocity as calculated by the numerical code is 3.5% and the
spread in streaming velocity is 6.8%.

An overall sketch of the traveling wave amplifier in which
this electron gun will be employed is shown in Fig. 6. In essence, it
combines the magnetron injection gun which characterized the Soviet
work (see Fig. 3) with the input wave launcher and traveling wave inter-
action of the NRL intense beam amplifier (see Fig. 2). It is expected
that this approach could lead to devices which are characterized by the
megawatt peak power levels of Table 1 combined with the high effi-
ciencies of Table 2.

Lastly, it should be noted that a superconducting magnet is
being employed in the 8 mm device of Fig. 6. This will allow for future
experiments at higher frequency. Preliminary designs are in progress
for cyclotron masers which would generate 100-200 kilowatts at $\lambda = 2.4$
mm at the fundamental of the cyclotron frequency, and kilowatts at $\lambda = $

1 mm at the 4th cyclotron harmonic. These higher frequency gyrotrons will

be of the single-cavity oscillator type as in the Societ work.

IV. BEAM-WAVE SCATTERING MECHANISMS

Finally, a third class of microwave sources involving pulsed technology is related to coherent backscattering of electromagnetic radiation from intense, relativistic-electron beams. These experiments are illustrated in Fig. 7. They fall into two types, mirror-like scattering from the rapidly rising front edge of the beam and stimulated scattering from induced electron density oscillations in the body of the electron beam. In both types of scattering a Doppler shift occurs, giving a strong upshift in frequency.

In both methods, the frequency of the backscattered wave ω_s is related to the frequency of the incident wave, ω_i by the relationship

$$\omega_s = (1 + \beta)^2 \gamma^2 \omega_i ,$$

where β and γ are the normalized velocity and normalized total energy of the electrons, respectively, i.e., $\beta = v/c$ and $\gamma = 1 + (T/mc^2) = (1 - \beta^2)^{-1/2}$. Here T is the electron kinetic energy. It should be appreciated that the Doppler shift can be large; for example, with 2 MeV electrons $\gamma \approx 5$ and $\beta \approx 1$ so that $\omega_s \approx 100 \ \omega_i$ and an incident wave with a wavelength of 3 cm would yield a backscattered wave at 300 μm. Moreover, the output wavelength is adjustable by changing either ω_i or the electron energy. Thus, devices based on coherent scattering promise to provide continuously-tunable, coherent sources at submillimeter wavelengths where no such sources are presently available. We propose to name such devices DOPPLERTRONS.

11

Unlike other common mechanisms for frequency conversion (e.g. harmonic generation in nonlinear components, or submillimeter generation in optically-pumped molecular lasers) the Dopplertrons promise energy and power gain. The energy of the backscattered output wave, W_s, is related to the energy of the input wave, W_i, by

$$W_s = (1 + \beta)^2 \gamma^2 R W_i,$$

where R is the reflectivity of the beam (i.e. the fraction of incident photons which result in backscattered photons). Clearly when the reflectivity approaches unity energy gain may be achieved that is almost as large as the Doppler frequency shift. Moreover, in the beam-front scattering version of the Dopplertron, relativistic time compression also occurs and thus the power gain will be larger than the energy gain by an additional factor of $(1 + \beta)^2 \gamma^2$.

The interesting features of e. m. wave interaction with a reflector moving at relativistic speeds was first recognized by Albert Einstein in 1905.[32] In 1952, Landecker[33] described how the front of a magnetized relativistic electron beam could provide such a relativistic reflector. However, an experimental demonstration of beam front scattering was not made until 1976. A group at NRL demonstrated the conversion of a 3 cm incident wave into a 1 cm output wave with output power being twice as large as incident power.[34] In more recent studies at NRL,[35] the velocity of the beam-front electrons has been increased by steepening the rise time of the accelerating voltage pulse. This has resulted in a demonstration of converting a 3 cm incident wave into a 6 mm output wave with power in the output wave exceeding incident

12

power by more than an order of magnitude. Moreover, in these recent experiments energy gain was achieved as well as power gain.

The beam front scattering process thus appears to be attractive for producing very high-power, high frequency pulses. However, it has a feature which may be a drawback in many practical situations: the output pulses produced are very short in duration. The scattering only occurs for the time it takes the beam front to propagate through the limited length of the interaction region, L, and in addition there is a relativistic time compression. Thus the duration of the output pulse is only $L/(v(1 + \beta)^2 \gamma^2$, typically on the order of one nanosecond.

The second type of scattering, stimulated scattering from induced density fluctuations in the body of the electron beam, is not characterized by short output pulses, and can in fact produce an output pulse as longlasting as the electron current pulse. This scattering process involves an instability in which the pondermotive force (radiation pressure force) generated by interaction between the incident and scattered e.m. waves modulates the beam electron density; this modulation in turn produces stronger scattering. The growth of the instability depends on the strength of the incident pump wave, and for e-folding lengths on the order of centimeters, one normally requires pump wave power at a level $\geqslant$ 10 MW/cm^2.

The production of submillimeter radiation by stimulated scattering of a microwave signal from a relativistic electron beam was first proposed by Pantell.[36] Subsequent theoretical analyses included the effect of boundaries,[37] of an external magnetic field,[38,39] and of collective plasma effects.[39,40] An initial experimental study at NRL

has used an incident 2 cm wave at a power of $\sim$ 100 MW to yield a 1 MW scattered wave at 400 μm.[41] Improved experiments are in progress with the aim of producing still higher power submillimeter pulses with better efficiency.

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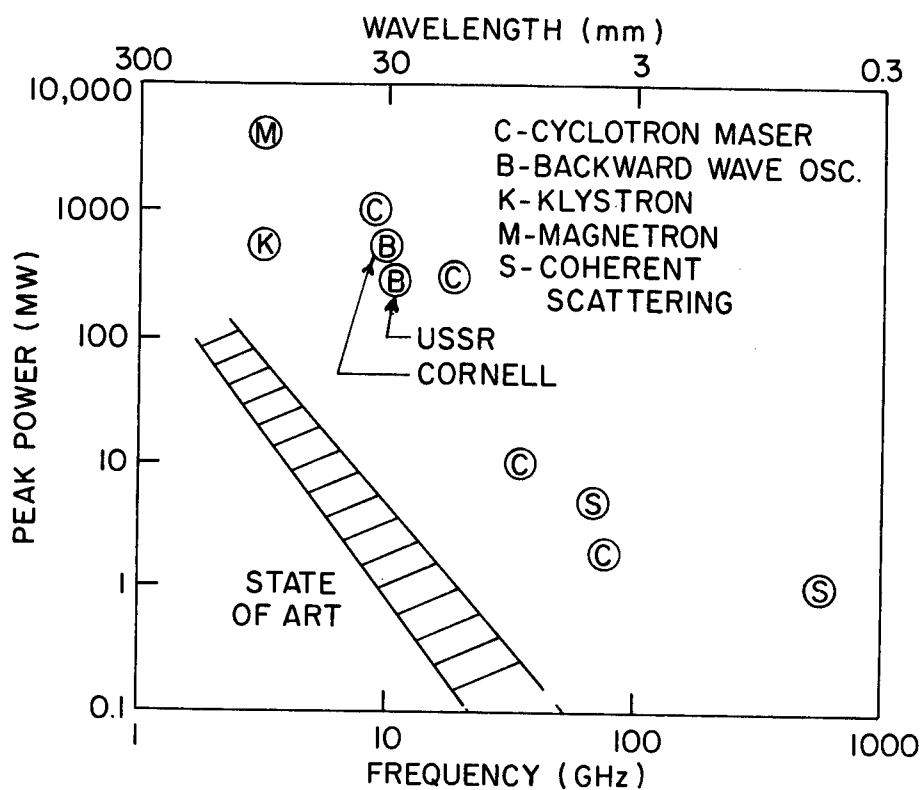42. M. Friedman and M. Herndon, Phys. Fluids 16, 1982 (1973).

Fig. 1 - Peak power vs frequency for intense, relativistic electron beam (IREB) experiments compared with state-of-art microwave tubes. Typical IREB pulse length: 50 nsec. The cyclotron maser result at 1000 MW, 9 GHz refers to a collaborative NRL/Cornell University experiment (Ref. 14). The magnetron result at 4000 MW, 3 GHz refers to an MIT/NRL collaboration (Ref. 3). All other unmarked points are from NRL results (see text for references).
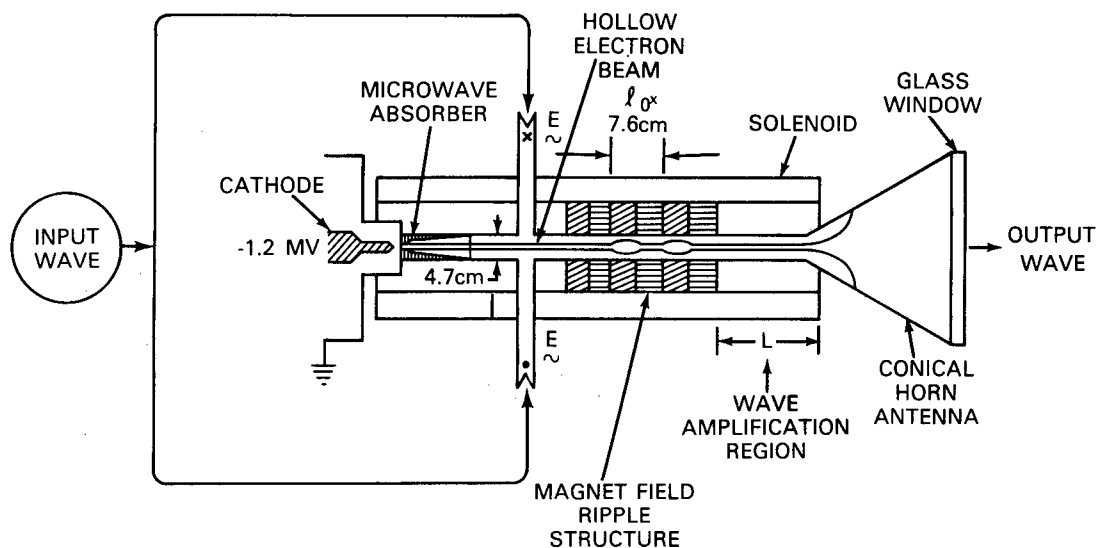
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OUTPUT
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INPUT
WAVE

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WAVE
AMPLIFICATION
REGION

CONICAL
HORN
ANTENNA

MAGNET FIELD
RIPPLE
STRUCTURE

Fig. 2 - Cyclotron maser distributed-interaction amplifier using an intense relativistic electron beam. Input signal from magnetron was coupled into the drift tube in the TE_{01} mode. The ripple structure consisted of alternating iron and aluminum rings which perturbed the magnetic field lines and imparted large transverse energy into the growing TE_{01} wave. The length of the system from cathode to output window was about 3 meters.
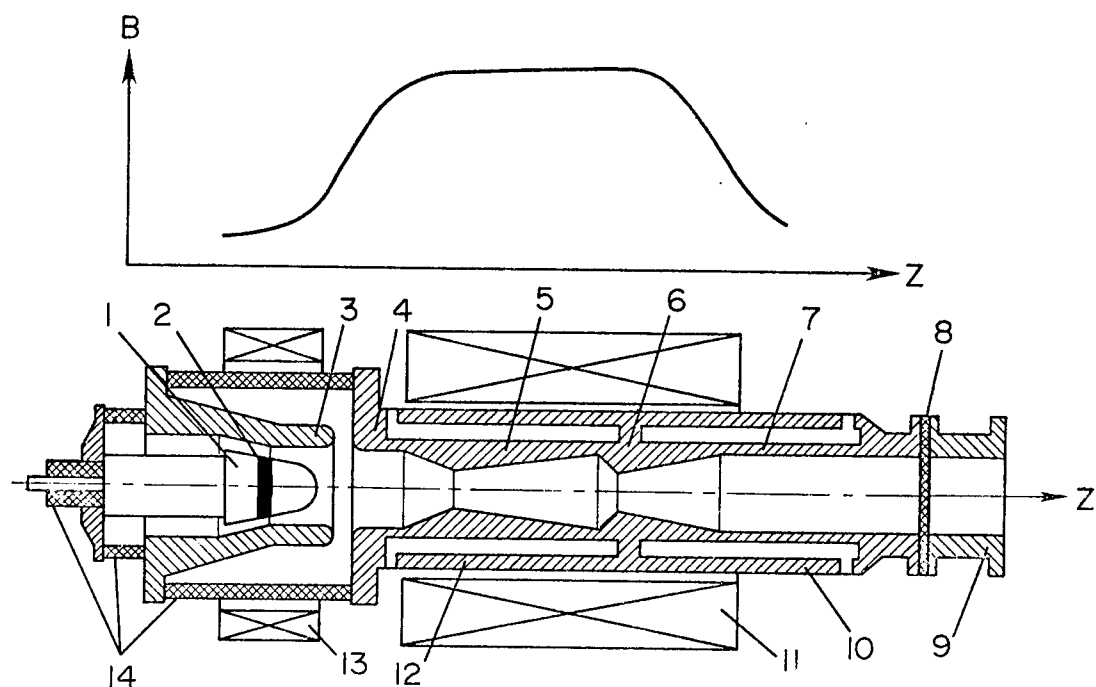
Fig. 3 - Outline drawing of Soviet gyrotron prototype. 1 - cathode;
2 - emitting strip; 3 - first anode; 4 - second anode; 5 - cavity;
6 - output coupling aperture; 7 - beam collector; 8 - output window;
9 - output waveguide; 10 and 12 - water jackets; 11 - main solenoid;
13 - electron gun solenoid; 14 - insulators. Overall length of this
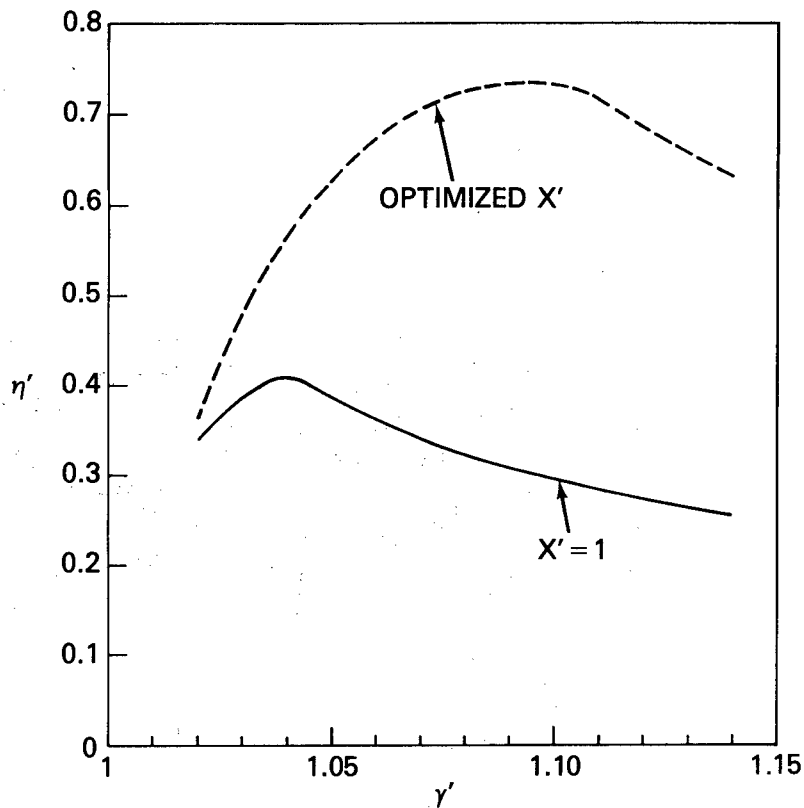device is approximately 20 cm.

Fig. 4 - Calculated efficiency of cyclotron maser amplifier vs initial transverse electron energy, expressed in kilovolts, for beam current of 10 amps (from calculations based on theory in Ref. 23 and 30). Solid curve: cyclotron frequency = input wave frequency (TE_{01} mode); dashed curve; cyclotron frequency detuned 3% by reducing magnetic field. The calculations shown here have been used to design an efficient 35 GHz distributed amplifier at the 200 kW level.
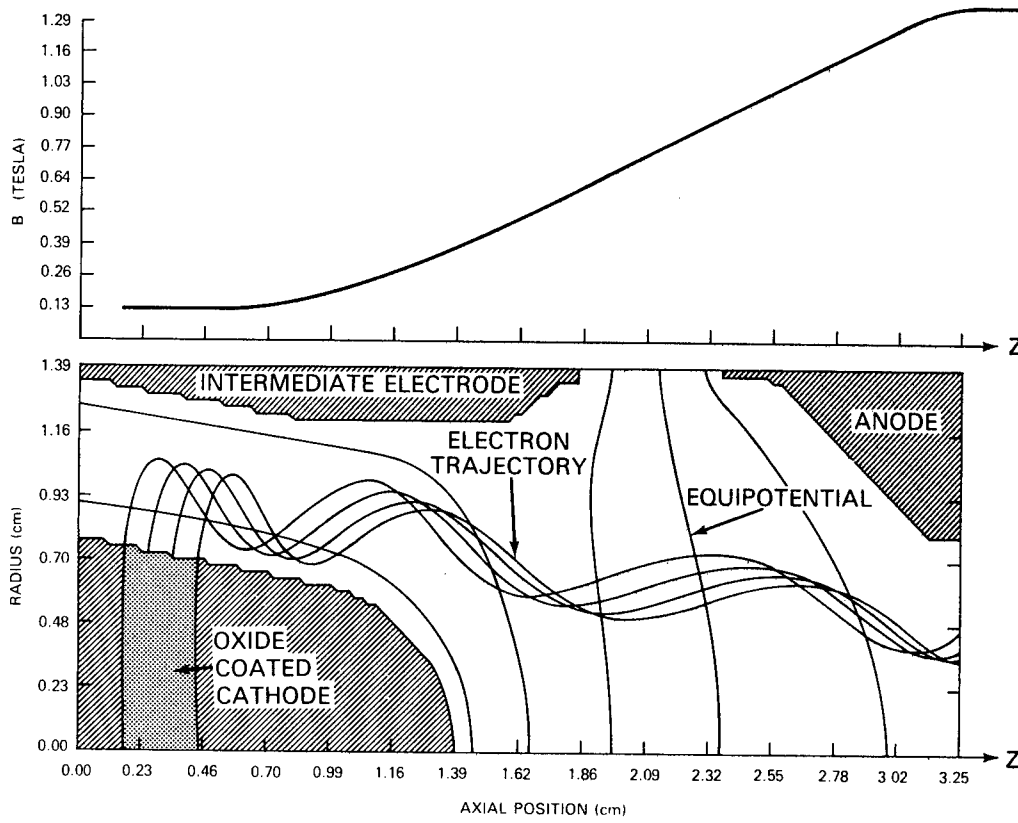
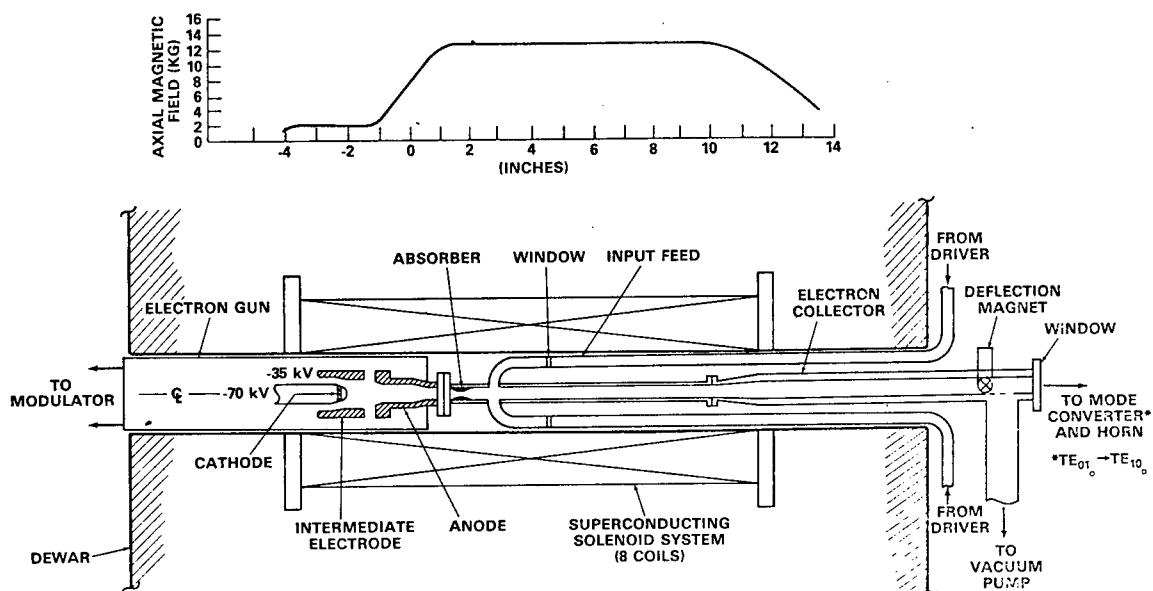Fig. 5 - Computer design of electron gun for 35 GHz distributed
amplifier.

Fig. 6 - Sketch of the planned NRL Gyro-Traveling Wave Amplifier (TE_{01}^{o} mode 35 GHz operating at the fundamental of the cyclotron frequency). The solenoid is of the superconducting type.